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Compaction conditions greatly affect growth during early plant establishment

C.T.S. Beckett[a,], D. Glenn[a], K. Bradley[a], A.L. Guzzomi[c], D. Merritt[b], A.B. Fourie[a]

[a]*School of Civil, Environmental and Mining Engineering, University of Western Australia, Perth, WA*
[b]*Botanic Gardens and Parks Authority, Kings Park and Botanic Garden, Perth, WA*
[c]*School of Mechanical and Chemical Engineering, University of Western Australia, Perth, WA*

Abstract

Successful plant establishment is critical for the success of store/release cover systems. Such cover systems comprise several soil layers: highly compacted lower layers to isolate the waste; and nominally-loose upper layers to support vegetation. However, compaction of the upper layers under heavy machinery is often unavoidable, retarding plant growth and compromising the system's ability to capture infiltration.

It is well known that compaction at different water contents imparts differing soil microstructures as well as densities. However, how to take advantage of those microstructures to mitigate compaction's effect on plant growth has yet to be investigated. This paper presents results for the growth of *Avena sativa* (oats) under different compaction conditions. Seeds were planted in soil columns comprising a sandy or clayey soil or layers thereof and allowed to grow under controlled climatic conditions for seven weeks. Plants were then extracted to examine the effects of compaction on plant features (root length and mass and shoot mass). Soil apparent hydraulic conductivity (unvegetated) was also measured. Results showed that compaction at the optimum water content, typical of geotechnical practice, was the most detrimental for plant growth. Rather, plant growth was greatest for compaction conditions which imparted both a lower dry density and hydraulic conductivity, for example typical of compaction at water contents above optimum. Results therefore highlighted the need to consider all facets of compacted soil texture when estimating the likely success of plant establishment.

Keywords: Soil compaction, soil microstructure, root growth, cover design

1. Introduction

Soil compaction is an important issue for modern store/release covers. Their primary function is to restrict net infiltration to reduce long-term seepage, acidification and oxidation of underlying waste (Rajesh et al., 2014). To achieve this, multiple soil layers are deposited and compacted to reduce their hydraulic conductivity. However, the store/release system relies upon an upper layer of vegetation to intercept infiltration, store it in the upper soil layers and release it via evapotranspiration (Campbell, 2004). Topsoil is placed in a nominally *uncompacted* state to maximise water storage capacity and evaporative loss during dry periods. However, in many cases, compaction is difficult to avoid due to the use of heavy plant, which can severely impact plant survivability (Unger and Kaspar, 1994; Cui et al., 2010; Lamandé and Schjønning, 2011a,b,c).

The effects of compaction on soil properties can be physical, chemical or biological. The most obvious physical effect is an increase in soil strength and a

Email addresses: christopher.beckett@uwa.edu.au (C.T.S. Beckett), dane_glenn@hotmail.com (D. Glenn), Kyle.bradley@brookfieldmultiplex.com (K. Bradley), andrew.guzzomi@uwa.edu.au (A.L. Guzzomi), David.Merritt@bgpa.wa.gov.au (D. Merritt), andy.fourie@uwa.edu.au (A.B. Fourie)

consequent reduction in the amount of friable substrate available to plant roots. Increased penetration resistance limits root exploration and can significantly alter root architecture as well as plant growth rates and seedling establishment (Henderson, 1989; Harrison et al., 1994; Rokich et al., 2001; Siegel-Issam et al., 2005; Benigno et al., 2012). Although some beneficial effects of compaction have been reported (e.g. increased nutrient transfer due to increased soil-root contact area, Carter (1990)), such effects are for levels of compaction below those commonly encountered in trafficked areas (Hamza and Anderson, 2005). Rather, compaction generally decreases soil fertility by reducing the store and supply of nutrients and water while reduced oxygen diffusion through the soil profile can result in de-nitrification and decreased micro-organism activity (Renault and Stengel, 1994).

For a given compactive effort (that is, the compacting energy delivered to the soil), a maximum soil dry density exists at a corresponding Optimum Water Content (OWC). Compaction water contents above or below this value produce lower dry densities for the same compactive effort. Reduced dry density either side of the OWC is due to changes in aggregate strength and soil suction. Dry of optimum, soils generally comprise small, strong aggregates of reduced deformability, preventing compaction. Wet of optimum (near and above field capacity), aggregates are large, highly saturated and deformable. Compaction under these conditions is restricted by high volumes of incompressible water (Cetin et al., 2007; Tarantino and De Col, 2008). Changes in aggregate strength with water contents above or below the optimum value result in different characteristic compacted microstructures (i.e. aggregate arrangement); generally, soils compaction dry of optimum comprise significant inter and intra-aggregate pore volumes whilst those compacted wet of optimum nominally comprise intra-aggregate pores only

(Delage, 2010; Alaoui et al., 2011). A single dry density can therefore characterise multiple soil microstructures. Although limiting subsoil densities for root growth impedance have been suggested by several authors (Daddow and Warrington, 1983; Jones, 1983; Siegel-Issam et al., 2005; Dal Ferro et al., 2014), what effect changes in microstructure may have on root growth has not yet been considered.

This paper investigates the effect of changes in compaction water content and density on early root growth of *Avena sativa* (oats) in a sandy and a clayey Western Australian agricultural subsoil. Seeds were planted in growth columns comprising either a single soil or layers of both soils, compacted to different conditions on the Standard Proctor curve. Results demonstrated a significant effect of compaction condition on plant performance, doubling root and shoot mass between the most and least beneficial cases. The experimental programme used in this investigation is described in the following section, after which results are presented and discussed.

2. Experimental programme

2.1. Material selection and compaction conditions

Two soils were obtained from the Northam region of WA. Northam is classed as category Csa under the Köppen-Geiger Climate Classification and has a mean annual rainfall of 427mm, predominantly falling in the winter months (June to August) (Australian Government Bureau of Meteorology, 2015). "Soil A" is a sand, obtained from an elevated site. "Soil B" is a clayey loam, obtained from a nearby valley (United States Department of Agriculture classifications). Both soils were overlain by a 100mm layer of topsoil, which was removed prior to collection as per common geotechnical practice. Particle grading curves for Soils A and B are shown in Figure 1.

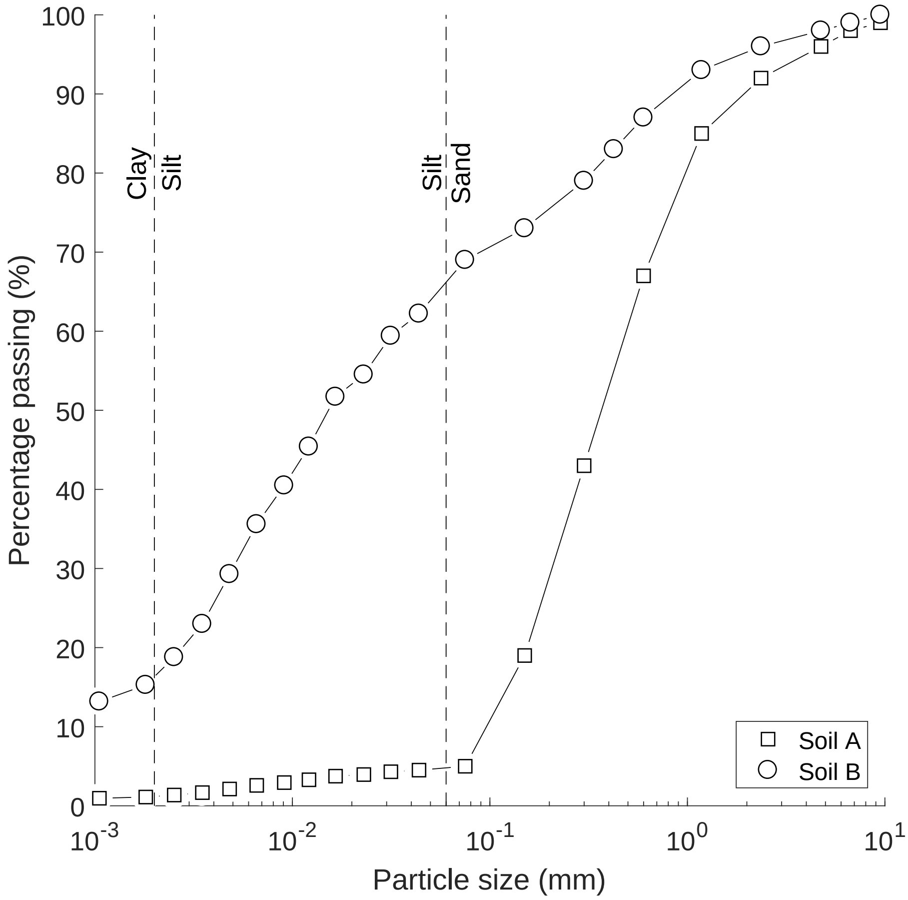

Figure 1: Particle size distributions: Soil A (sand) and Soil B (clayey loam)

(Insert Figure 1 somewhere near here)

Compaction curves for both soils are shown in Figure 2, determined using the Standard Proctor Test (SPT, AS1289.5.1.1). Håkansson et al. (1988); Håkansson (1990) argued that the SPT overestimated compaction under 20th century agricultural vehicles. However, Suzuki and Reinert (2013) demonstrated that the SPT accurately captures compaction at a depth of roughly 100mm beneath heavier 21st century vehicles, as might be used on remediation sites. The SPT is also familiar to geotechnical engineers, expediting comparison to existing engineering literature and practice. Hence, the SPT was selected to examine effects of compaction conditions on root growth. Compaction curves for Soils A and B are shown in Figure 2. Four compaction conditions were tested per soil:

1: $\rho_d = \rho_{d_{max}}$, w <OWC

2: $\rho_d = \rho_{d_{max}}$, w =OWC

3: $\rho_d < \rho_{d_{max}}$, w >OWC

4: $\rho_d < \rho_{d_{max}}$, w =OWC (Soil A) $\rho_d < \rho_{d_{max}}$, $w_4 = w_1$ (Soil B)

where w is the compaction water content. Condition 2 is typical for geotechnical construction, as it achieves the highest dry density and strength. Condition 3 may occur if traffic immediately follows heavy rain (as occurs in rural Australia, Campbell (2004)). Condition 1 shared a dry density with Condition 2 (i.e. the maximum dry density) but was at a lower water content to encourage a more aggregated microstructure. For Soil A, Condition 4 investigated compaction at the same water content as Condition 1 but at the same compactive effort used for Conditions 2 and 3 (i.e. Conditions 2, 3 and 4 fell on the compaction curve). For Soil B, a similarly-defined Condition 4 was too close to Condition 1. Condition 4

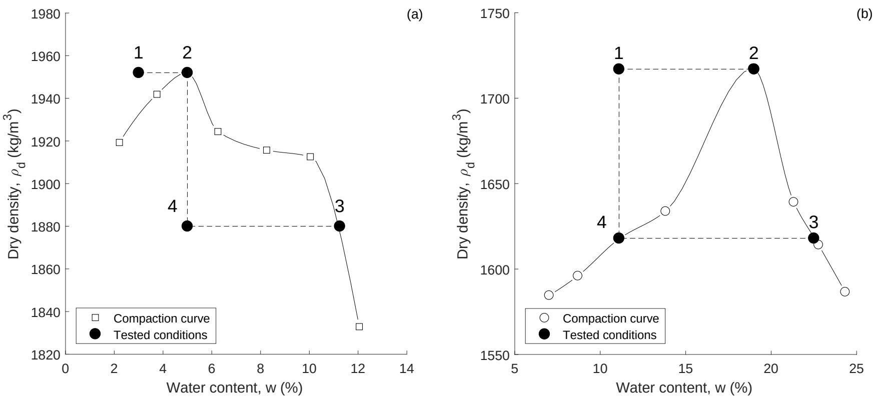

Figure 2: Compaction curves: a) Soil A; b) Soil B. Testing compaction conditions 1, 2, 3 and 4 are also shown.

therefore investigated a water content equal to the OWC but a dry density equal to Condition 3 (i.e. sub-optimal compaction). As such, Conditions 1 & 2 and 3 & 4 shared equal compaction dry densities for both soils. Soils are henceforth referred to by their type and condition number, for example “A3”.

(Insert Figure 2 somewhere near here)

2.2. Growth columns

Growth columns were used to investigate root growth for each compaction condition. Columns were manufactured from 100mm internal diameter, 300mm tall sections of PVC pipe (wall thickness 5mm). One end was closed with a perforated plastic cap. Soil was compacted into the columns in five 50mm layers of controlled mass, volume and water content to achieve the target dry density. Columns contained either a single soil type or layers of both soils, as shown in Figure 3. Only one compaction condition was present per column; for example, five layers of Soil A1 or two layers of Soil A4 overlain by three layers of Soil B4.

Hereafter, columns are referred to either as single-soil or mixed and by the soil that formed the *uppermost* layers, e.g. “Soil A mixed columns”. Five columns were prepared per soil type combination and compaction condition (80 in total). Once compacted, columns were transferred to a curing room to equilibrate to atmospheric conditions of 98% relative humidity at 21°C until reaching a constant mass. These conditions were not selected to be representative of field conditions; rather, equilibration removed hydraulic gradients between layers compacted at different water contents (for example, conditions A2 and B2 did not share water contents) which may have affected seedling water uptake or availability. Columns were then wrapped in plastic film to prevent water and soil loss and transferred to the greenhouses at the Kings Park Botanic Gardens, Perth and arranged as a completely randomised block design (Fourie et al., 2008).

(Insert Figure 3 somewhere near here)

2.3. Hydraulic conductivity

Additional columns were manufactured for saturated hydraulic conductivity testing. As conductivity is affected by pore interconnectivity, measurements were used to qualitatively assess microstructural properties (Ellington, 1987; Stoltz and Greger, 2006; Romero, 2013). Conductivity column manufacture was as per growth columns, however height was increased to 500mm to accommodate a water head and end caps were removed after compaction and replaced with fine steel mesh to allow flow through the soil. Columns were not equilibrated to a target suction value. Rather, water was added to the top of the column following manufacture until a nominally-constant flow rate was achieved for a minimum of 30 minutes. Flow was then terminated and the water level allowed to decrease over a set period of time, t (a variation of the falling head method). “Apparent”

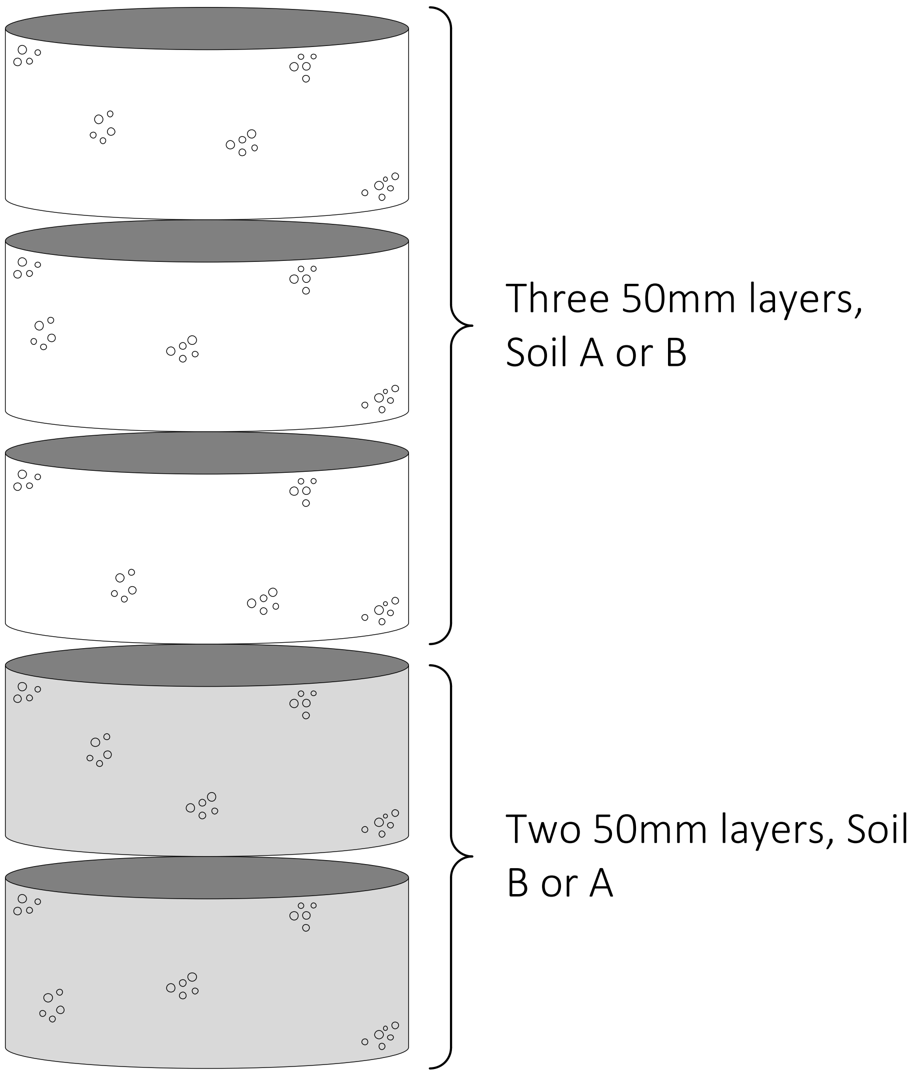

Figure 3: Soil layering in growth columns. Shading denotes layers comprising different soils (if present).

saturated hydraulic conductivity, $k_{apparent}$, was then determined using

$$k_{apparent} = \frac{L}{t} \ln \frac{h_0}{h_1} \tag{1}$$

where L is the length of the soil column (250mm) and h_0 and h_1 are the initial and final head levels (both higher than the soil surface to maintain saturation) respectively. Here we refer to "apparent conductivity" in preference to "saturated conductivity" as columns were not de-aired prior to testing: trapped air bubbles may have influenced conductivity values. De-airing or saturation under pressure was not attempted due to the column size. Mixed columns were not tested as flow through each soil type could not be distinguished using this technique. Tests per compaction condition were repeated four times for Soil A and twice for Soil B due to the lower flow rate.

2.4. Plant growth

Avena sativa (oats) was selected for these trials due to its fast-growing root system and history of cultivation at the Northam site. Soil nutrient status was not investigated however the strong growth history demonstrated that this species was suitable. (Campbell, 2004) indicated that drainage rates below cereal crops are a good indicator for rates beneath store-release covers in rural Australia. Three seeds were planted in each growth column, at a depth of 30mm. Seeds were not pre-germinated, nor was potting material added to the columns to ensure that any root growth was only affected by changes in compacted state. Columns were watered twice weekly at a rate of 72mL (9.2mm/m) per visit, equal to the long-term average rainfall for the month of July (growing season in WA) in Northam (Australian Government Bureau of Meteorology, 2015). It is noted that soil pore space available for water storage reduces as plants grow, affecting water availability. Accurate assessment of changes in water availability on plant growth prior to extraction was not possible as the root systems could not be examined. Therefore, a constant watering rate was used for the duration of the growing periods for consistency. Evaporation was minimised by maintaining a high humidity in the greenhouses via sprayers. Columns were not weighed during testing to avoid handling damage; evaporation rates were therefore assumed to be less than plant water needs.

Seedlings were reduced to one per column on reaching shoot heights of 50mm. If possible, spare seedlings of equal strength were transplanted to columns (with the same soil and compaction condition) where no growth was evident. Plants were monitored until the first evidence of roots reaching the base of the single-soil columns was noted: seven weeks in total. Plants and soil (both single-soil and mixed columns) were then extracted to prevent end caps from interfering with root distributions. A circular saw, set to the column wall thickness, was used to cut the columns lengthwise without damaging the roots (e.g. Figure 4). Soil was gently washed from the plants, submerging the soil for one hour to loosen it if necessary. Remaining soil particles were removed with tweezers and scaled photographs of each extracted plant taken for reference.

(Insert Figure 4 somewhere near here)

2.5. Root metric analyses

Plants were cut at the root-shoot interface to determine plant metrics. Root and shoot dry mass were determined by drying respective materials in paper bags placed in an oven held at 60°C for three days. Root length and volume with respect to diameter were measured using “WinRhizo” software. WinRhizo analyses images obtained using a flatbed scanner, e.g. Figure 5. Roots were

Figure 4: Extracted mixed Soil B3 column; soil layers are distinctly visible (3 Soil B3 layers (darker) overlying 2 Soil A3 layers (lighter)).

suspended in a thin film of water above the scanner to encourage separation; however, overlapping of neighboring roots was unavoidable. As roots were pressed against each other, variability in produced length and volume distributions was expected. Additional growth columns were therefore prepared to investigate the repeatability of WinRhizo analyses. Two A3 and two A4 columns were prepared and watered as per growth columns for other soils. Plants were extracted after 5 weeks and prepared for analysis as previously discussed. Roots were then scanned in two orientations orthonormal to each other with respect to the original column axis. Individual pieces of 2mm diameter cord (a simple root paradigm) were also scanned in multiple orientations and configurations to examine error in length measurement.

Placing extracted roots onto a flatbed scanner necessarily deforms their original structure. A further two A3 columns were therefore manufactured to examine methods to extract and measure the structure of *intact* root systems via oven drying. Plant shoots were removed after 5 weeks and the roots and soil dried in the sampling tubes at 105°C for 48 hours. Preliminary testing on loosely-compacted soil permitted roots to be extracted whilst preserving their in-situ structure. However, the highly-compacted A3 soil remained tightly bound to the roots, causing damage on removal. This technique was therefore not pursued but is reported here for future interest.

(Insert Figure 5 somewhere near here)

3. Results and discussion

3.1. WinRhizo repeatability

Repeatability results for 5-week Soil A single soil columns are shown in Figure 6. Average errors across all categories are also shown as dashed lines (- -).

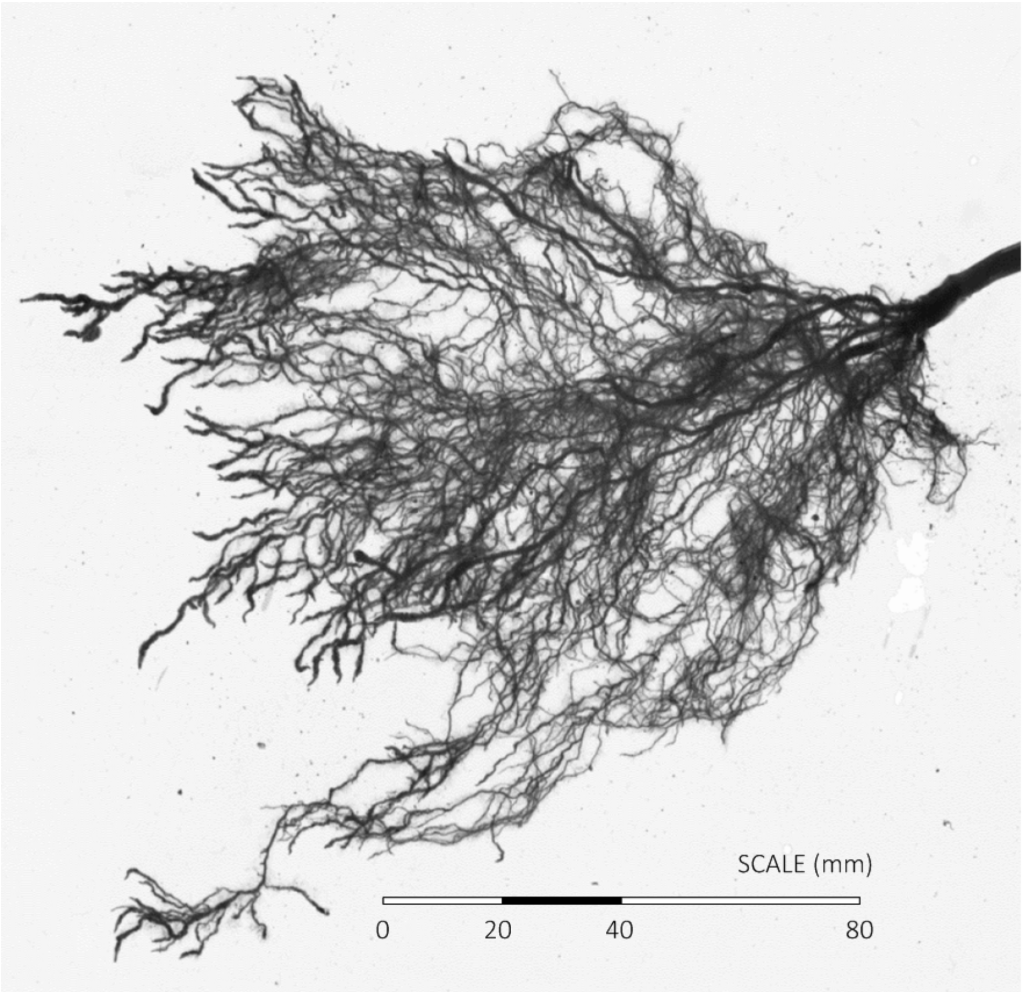

Figure 5: WinRhizo root scan (Column A4, extracted after 5 weeks)

Average error was similar for all columns (around 10%) but high variability between categories produced high standard deviations. By contrast, scans on pieces of cord revealed length errors of only 3%. Overall, larger root diameter classes were more susceptible to error, associated with clumping; individual roots adjacent to each other appear as a single root in the WinRhizo scan. A global error of 10% (determined from root length-weighted percentage error) was assumed for root length diameter categories. Notably, Himmelbauer et al. (2004) found that cereal crop (wheat) root length analyses were negligibly affected by root orientation. In that work, roots were stained prior to scanning. Staining may therefore have reduced uncertainty for roots analysed here. In the absence of staining and to reduce error, 7-week plant roots were scanned in an orientation judged to spread the roots out most effectively.

(Insert Figure 6 somewhere near here)

3.2. Single soil columns

Mean root length, shoot dry mass, root-shoot ratio and apparent hydraulic conductivities for single-soil columns are shown in Figure 7. Soil A and B root lengths are broken down by WinRhizo diameter category per compaction condition in Figures 8 and 9 respectively. An additional standard deviations of 8% was assumed for root length measurement, based on WinRhizo accuracies discussed in the previous section. Note that $k_{apparent}$ values were for the *unvegetated* soil; what effects plants had on hydraulic conductivity was outside the scope of this work, but has been investigated by other authors (e.g. Sinnathamby et al. (2014)). 1 and 2-factor ANOVA results per variable are given in Table 1.

(Insert Figure 7 somewhere near here)

(Insert Figure 8 somewhere near here)

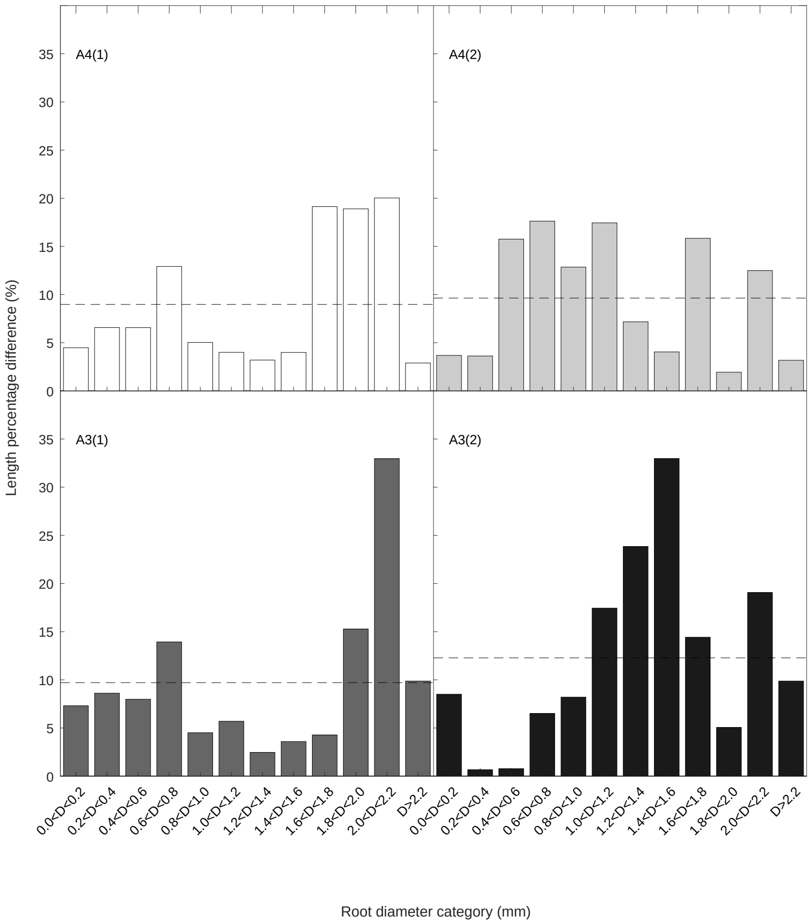

Figure 6: Percentage difference between orthonormal scans of Soil A3 and A4 root systems by root diameter category, D, after 5 weeks' growth. Dashed lines show average error over all categories. "SD" is the Standard Deviation.

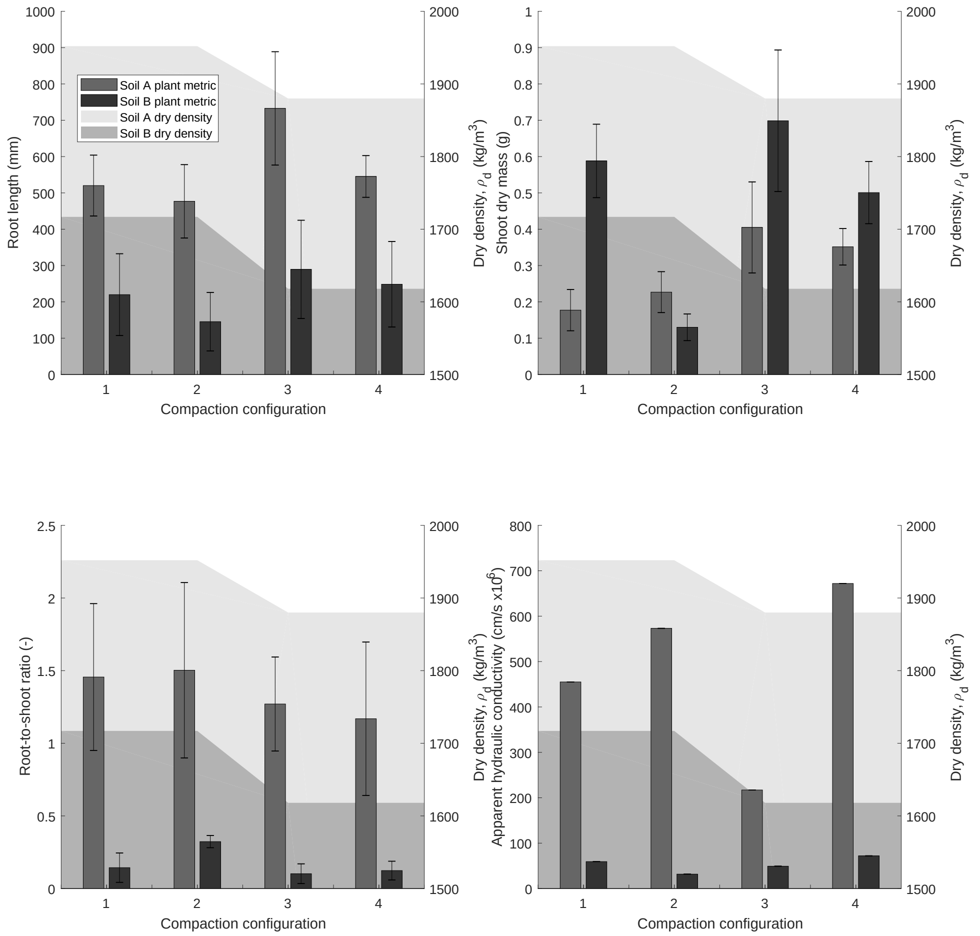

Figure 7: Single-soil columns: Root length, volume and dry mass, shoot mass, root:shoot ratios and hydraulic conductivities. Error bars show ±SD.

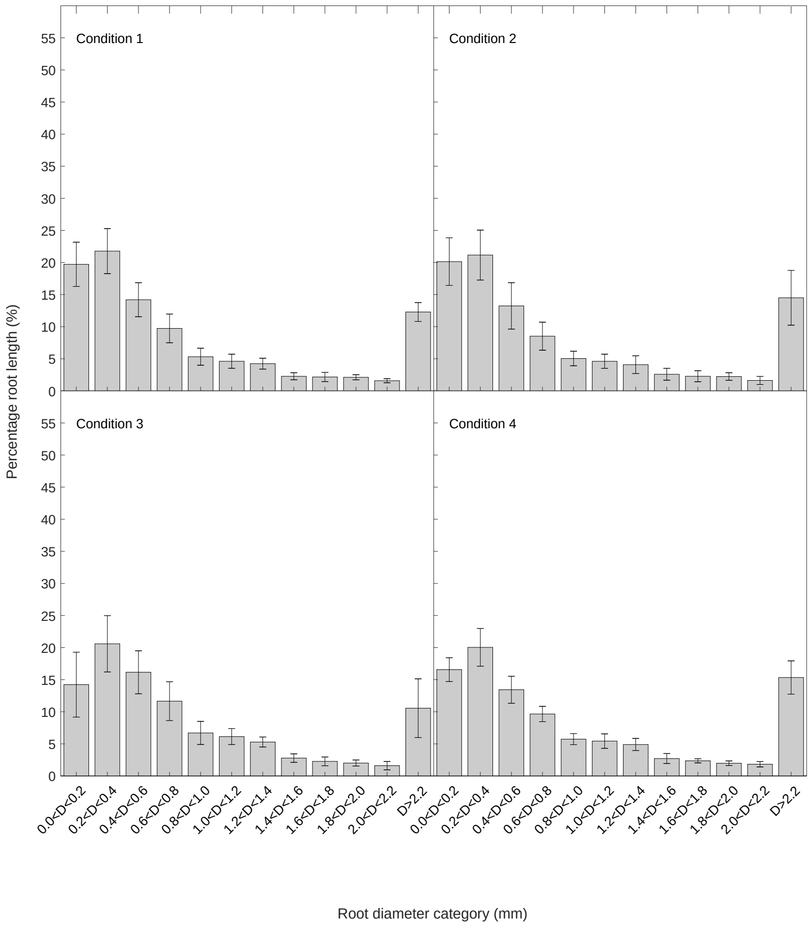

Figure 8: Single-soil columns: Soil A percentage root length by root diameter category per compaction condition. Error bars show ±SD.

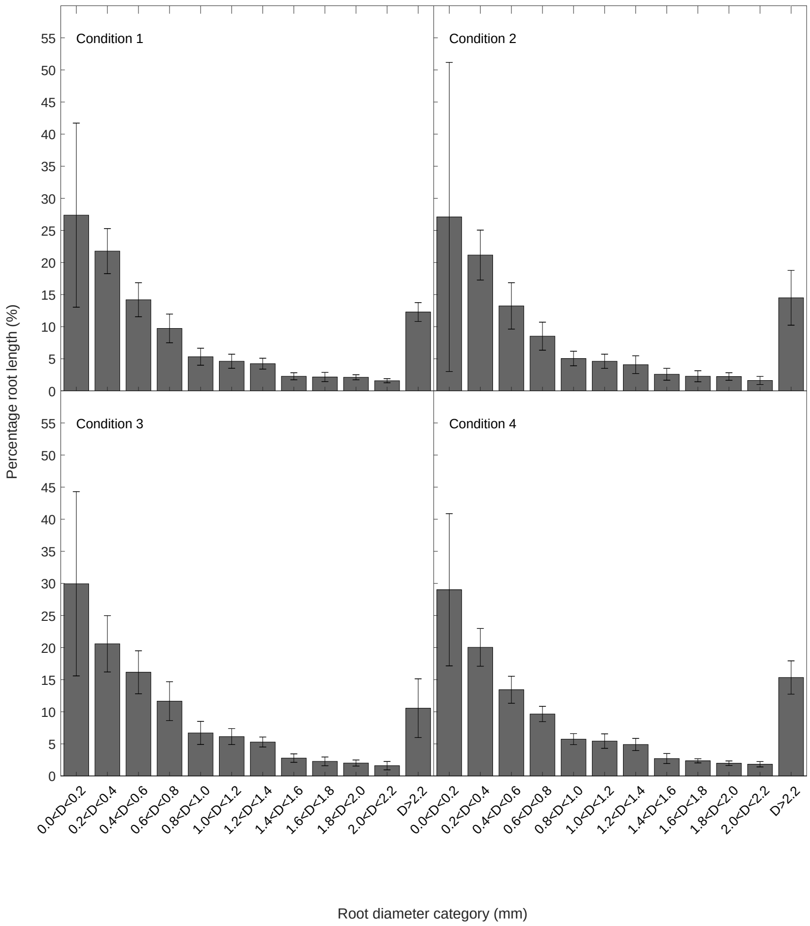

Figure 9: Single-soil columns: Soil B percentage root length by root diameter category per compaction condition. Error bars show ±SD.

Table 1: Single soil column 1 and 2-factor ANOVA results. CC: Compaction Condition; n/s $\equiv$ no significance; * $\equiv P < 0.05$; ** $\equiv P < 0.01$; *** $\equiv P < 0.001$.

	1-factor ANOVA		2-factor ANOVA		
Characteristic	Soil A CC	Soil B CC	Soil type	CC	Soil type×CC
Root length	**	n/s	***	**	n/s
Shoot dry mass	**	**	***	***	***
Root:shoot	n/s	***	***	*	n/s

(Insert Figure 9 somewhere near here)

(Insert Table 1 somewhere near here)

All Soil A columns produced visually-healthy plants (e.g. no shoot discolouration) and no water logging was observed. Soil A roots were similar to type VII by Cannon's classification (Cannon, 1949); dense, fibrous lateral roots with no obvious primary root (e.g. Figure 5). Soil A root lengths were similar for Conditions 1, 2 and 4, but significantly longer for Condition 3 (compacted above the OWC). Root diameter distributions were similar for all compaction conditions. Shoot dry mass was larger for Conditions 3 and 4 and doubled between the best and worst conditions (3 and 1 respectively). Root-shoot ratios were similar for all columns despite root and shoot mass changes: Bengough et al. (2011) reported similar results for maize.

Condition 3 had the lowest $k_{apparent}$ of all tested conditions, suggesting that Soil A root growth was strongly influenced by water retention Notably, neither $k_{apparent}$ nor root length were correlated with compacted dry density. Changes in $k_{apparent}$ for given dry densities indicate changes in soil microstructure due to different compaction water contents (Siegel-Issam et al., 2005). However, similar root diameter distributions between conditions suggests that each condition was equally resistive to root penetration: in the absence of microstructural or penetrometer data, though, such observations cannot be expanded upon further.

Seedling die-off was higher for Soil B than for Soil A; Conditions 2 and 3 were particularly affected due to waterlogging. Transplanting stronger seedlings permitted plants to be grown in each column. Soil B roots were similar to type VI by Cannon's classification (Cannon, 1949); as for type IV, a long primary root was present but lateral roots were significantly closer to the soil surface. Similar root diameter distributions were found for each compaction condition. Soil B roots were finer than for Soil A (higher percentage lengths in smaller diameter categories), suggesting either available pore spaces were smaller or increased water stress due to water logging (Bengough et al., 2011). Significantly shorter root lengths were found for Soil B than Soil A, with higher variability between specimens; this is typical of compacted clayey soils (Daddow and Warrington, 1983). As for Soil A, the highest root lengths and shoot masses were found for Condition 3. Root length, shoot mass and $k_{apparent}$ were similar for Conditions 1 and 4. Shoot dry mass for Condition 2 was significantly lower (roughly 25%) than for other conditions. However, root lengths and diameter distributions for Condition 2 were similar (although lengths were shorter) to those for other conditions; despite waterlogging, hypoxia was suggestibly avoided.

Plant growth was best for Condition 3 for both soils A and B: plants achieved the longest roots and highest shoot masses, i.e. providing the best conditions for water capture (Campbell, 2004). Critically, compaction at the OWC (Condition 2) which is typical for geotechnical structures, produced the *most detrimental* growing conditions. However, growth did not correlate with changes in dry density. Rather, compaction conditions imparting lower dry densities but also lower apparent hydraulic conductivities were preferred.

Table 2: Mixed soil column 1 and 2-factor ANOVA results. CC: Compaction Condition; n/s ≡ no significance; * ≡ $P < 0.05$; ** ≡ $P < 0.01$; *** ≡ $P < 0.001$.

	1-factor ANOVA		2-factor ANOVA		
Characteristic	Soil A CC	Soil B CC	Soil type	CC	Soil type×CC
Root length	***	n/s	***	**	**
Root dry mass	*	n/s	***	*	*
Shoot dry mass	***	*	**	n/s	***
Root:shoot	**	**	***	n/s	**

3.3. Mixed soil columns

Mixed columns investigated plant responses to sudden changes in dry density with depth, as may happen in cover systems with multiple soil layers or in tilled or ripped heterogeneous soils. Mixed column mean root length and mass, shoot dry mass and root-shoot ratios are shown in Figure 10. Root length diameter categories for each soil are shown in Figures 11 and 12. Again, an additional standard deviation of 8% was assumed for all root length measurements to account for WinRhizo inaccuracies. 1 and 2-factor ANOVA results for mixed columns are given in Table 2.

(Insert Figure 10 somewhere near here)

(Insert Figure 11 somewhere near here)

(Insert Figure 12 somewhere near here)

(Insert Table 2 somewhere near here)

All Soil A mixed columns produced healthy plants, as for single-soil columns. Again, roots were similar to Cannon's type VII; fibrous lateral roots were homogeneously spread to depths of 150mm with no obvious primary root. Similar root architecture indicated similar growing constraints between Soil A mixed and single-soil columns. Root systems for Conditions 1 and 3 were dominated by diameters <0.2mm. Root systems for Conditions 2 and 4 were also fine, dominated

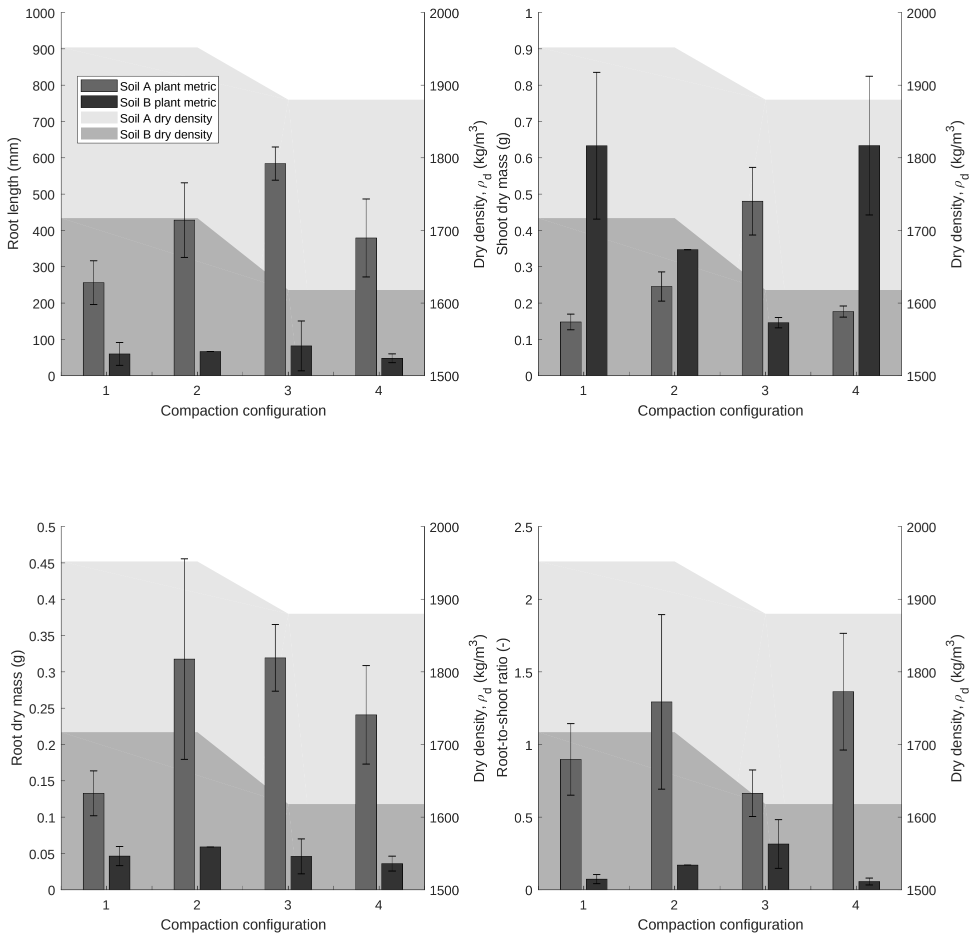

Figure 10: Mixed soil columns: Soil A and B root length and dry mass, shoot mass and root:shoot ratios. Error bars show ±SE.

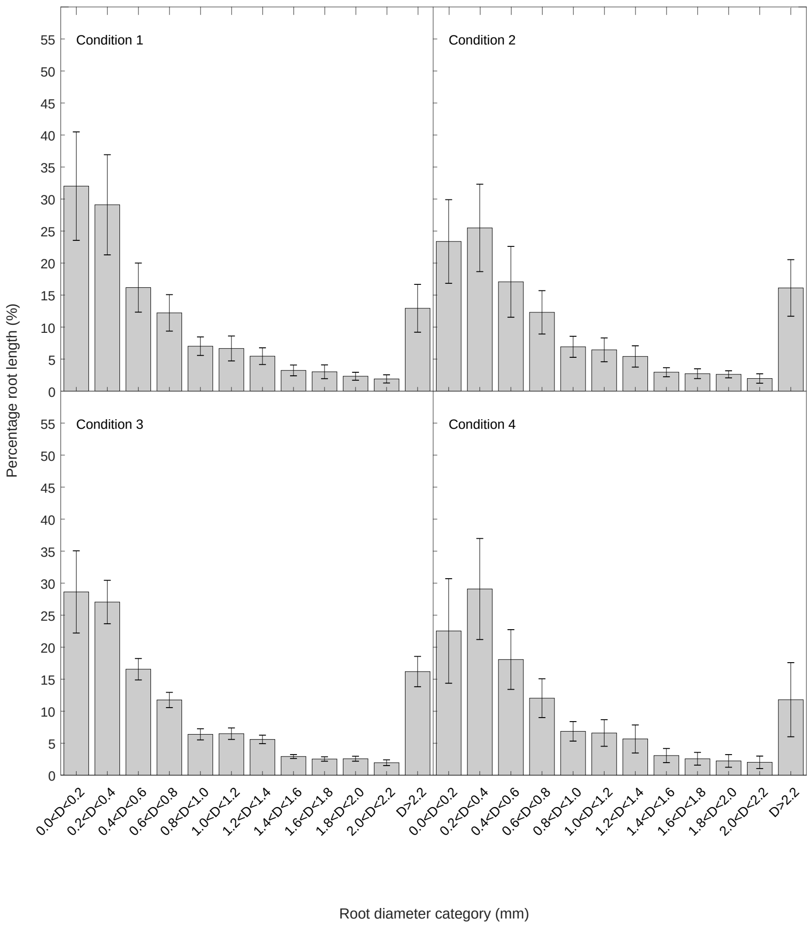

Figure 11: Mixed soil columns: Soil A percentage root lengths per compaction condition. Error bars show ±SD.

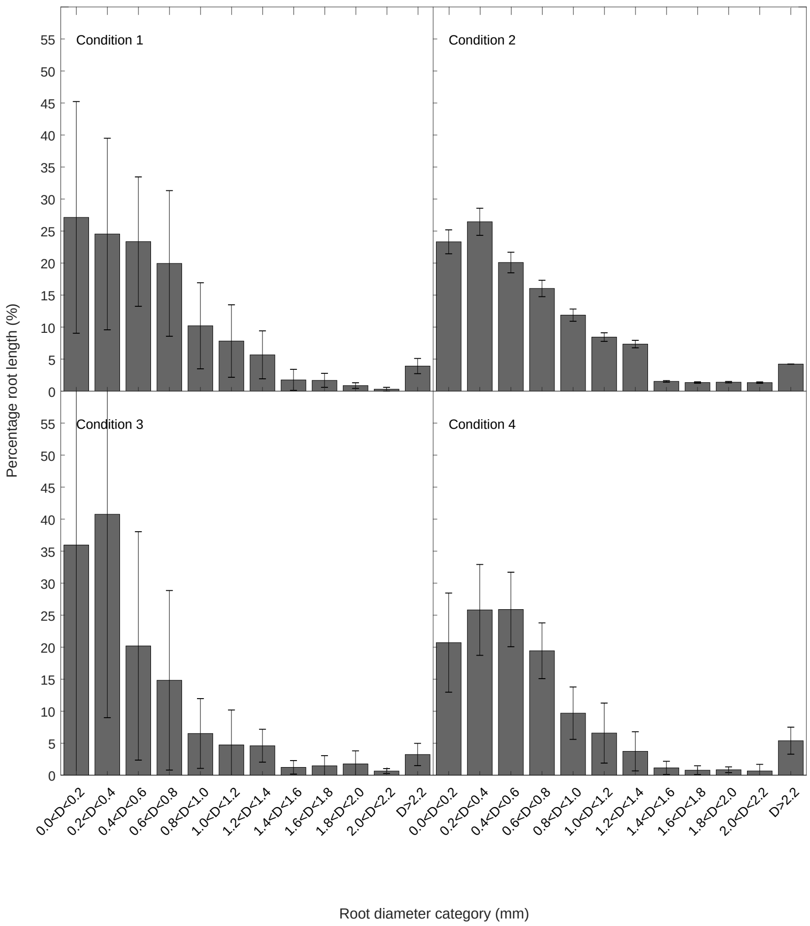

Figure 12: Mixed soil columns: Soil B percentage root lengths per compaction condition. Error bars show ±SD.

by diameters 0.2–0.4mm.

On extraction, roots were found growing parallel to the Soil A-B interface (i.e. perpendicular to the column axis). Notably, this demonstrated a preference for the *higher* dry density layer. Such a response is likely due to the difference in root architecture previously discussed for Soils A and B; the strong primary root necessary for growth in Soil B was not present and so lateral roots preferentially remained in the Soil A layer.

Overall, shorter root lengths were found for mixed columns with Soil A uppermost than in Soil A single-soil columns. Significant differences were found between root length and mass and shoot mass at each compaction condition; again, shoot mass more than doubled between the best and worst cases. Maximum root growth and shoot dry mass was found for Condition 3. Condition 2 produced similar metrics to Condition 4 despite a higher dry density. Condition 1 consistently produced the lowest plant metrics. That Conditions 2 and 4 were similar but 1 and 3 were not was likely due to differences in $k_{apparent}$ (Figure 7d); water retention for Condition 3 was superior to that for Condition 1 (as judged by lower permeability) but similar between Conditions 2 and 4. As for single-layer columns, plant metrics did not correlate with dry density.

Plant growth in Soil B mixed columns was poorer than in single-soil columns for all tested conditions, as for Soil A. Roots were similar to Cannon's type VI; a strong primary root with few isolated lateral roots near the surface. The strong primary root in Soil B columns *penetrated past* the Soil B-A interface but did not thereafter produce lateral roots. Root diameter distributions were similar per compaction condition but were highly variable for Condition 3, perhaps due to damage on extraction. The strongest plants were found for Conditions 1 and 4; Conditions 2 and 3 experienced high mortality rates due to waterlogging.

Notably, Condition 3 produced the lowest shoot masses despite producing the highest shoot masses in single-layer columns. Soil may therefore have been over-compacted. No significance was found between root length or dry mass between compaction conditions.

Plant growth in the mixed columns was complicated by the more complex growing conditions. However, once again, plant growth *did not correlate solely with dry density*. Condition 3 (compaction above the OWC) produced the most beneficial growth conditions for Soil A: a lower dry density but also lower hydraulic conductivity. Contrariwise, Condition 3 produced the *worst* growth conditions (by shoot mass) for Soil B. Rather, potential over-compaction of Soil B led to optimised performance at higher apparent hydraulic conductivities. Mixed column results therefore supported the findings from the single-columns: dry density and hydraulic conductivity are both critical factors dominating plant growth.

4. Conclusions

Modern cover systems often incorporate vegetation for stability, protection and/or land rehabilitation. Proper design of these structures/landscapes must consider the role of the soil both as a moisture barrier and a supporting layer for vegetation. This paper investigated the growth of *Avena sativa* in soils compacted to different conditions relative to the Standard Proctor compaction curve, representative of compaction under heavy 21st century plant. Plant growth metrics more than *doubled* between the most and least beneficial compaction conditions tested. Single-soil column results demonstrated that improved growth was associated with lower density *and* lower apparent hydraulic conductivity, indicative of improved water storage. Contrariwise, compaction at the OWC, typical for geotechnical applications, resulted in the *poorest* plant growth. Mixed columns investigated more complex growing conditions. Plants grown in Soil A mixed columns displayed similar metrics to those in single-soil columns: lower dry densities and hydraulic conductivities produced the most beneficial growing conditions. Again, compaction at the OWC produced the worst results. Plants grown in Soil B mixed columns were weaker, likely due to overcompaction: Soil B plants preferred higher hydraulic conductivities as waterlogging was avoided. Plant growth therefore did not correlate solely with changes in dry density. Rather, results highlighted the importance of soil texture, being density *and* particle arrangement, to the success of early plant establishment.

5. Acknowledgements

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